Magnetospheric Undulations Sonified Incorporating Citizen Scientists

Dr Martin Archer

School of Physics and Astronomy, Queen Mary University of London

Abstract

The magnetosphere is the dynamic space environment due to the interplay of the solar wind with Earth's magnetic field. The equivalent to sound in space, plasma waves in the ultra-low frequency (ULF) range (< 1 Hz), are present throughout this region. Many questions concerning ULF waves still remain, such as how often and at what frequencies do various resonances of the magnetosphere occur. This research project allows you to study these waves by using perhaps the best pattern recognition system that we know of, the human auditory system. By listening to satellite data and using audio software you will explore the waves present in near-Earth space and undertake your own research project, the findings of which could contribute to improving our understanding of magnetospheric ULF waves.

1 Introduction

Earth's **magnetosphere** is the space environment around the Earth formed by the interaction of the solar wind (plasma continually streaming away from the Sun at supersonic speeds) with the Earth's magnetic field. The solar wind compresses this magnetic field on the dayside, confining it to typically within 10 times the Earth's radius ($\mathrm{R_E}$), whereas it sweeps back the magnetic field lines on the nightside to some unknown length, possibly up to 1000 $\mathrm{R_E}$. In turn the solar wind is itself slowed and deflected around the magnetic barrier (by a shock wave, the bow shock, due to its supersonic speed). Figure 1 illustrates some of the basic structure of the magnetosphere.

The magnetosphere is far from static, for example the solar wind pressure and magnetic field continually change causing the size and shape of the magnetosphere to adjust accordingly. One of the dynamic aspects of the magnetosphere are the number of different **plasma waves** that can be supported. In the **ultra-low frequency** (ULF) range, defined as waves/oscillations of frequency <1 Hz, the plasma can be treated as a single fluid in much the same way as air or water. This means there are two fundamental types plasma waves:

- **Magnetosonic waves**: the equivalent of sound waves in plasmas, however, unlike a gas in which sound is driven by thernal pressure only, plasmas also exhibit magnetic pressures too hence the name of these waves. These waves can have both longitudinal and transverse components and can transport energy across magnetic field lines.

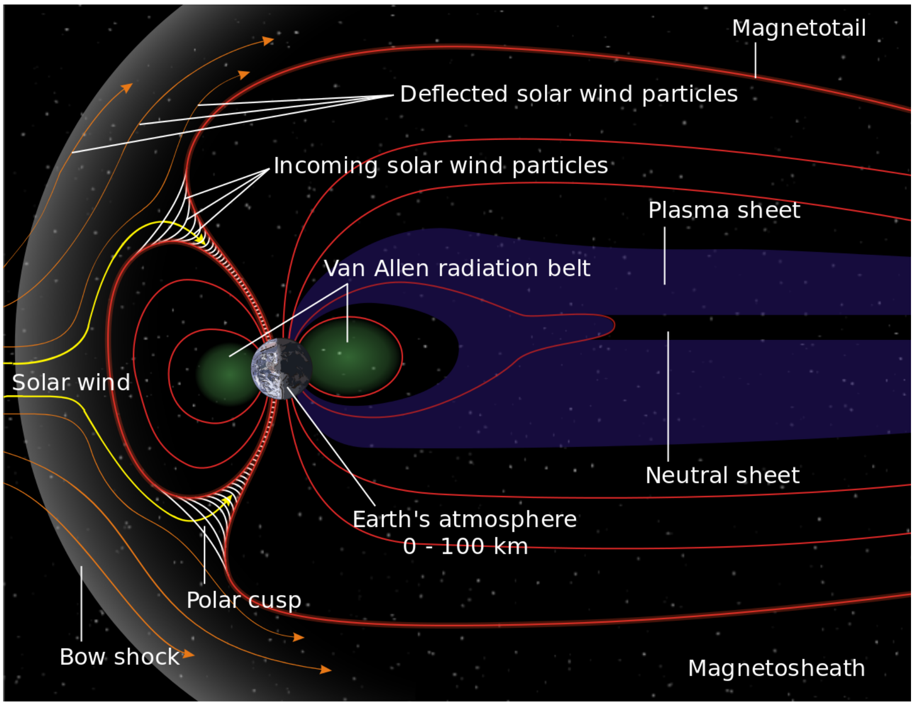

Figure 1: Structure of Earth's magnetosphere.

- **Alfvén waves**: a sister wave not possible in gases, these are analagous to waves on a string since magnetic field lines in a plasma exhibit a form of tension. Their wave perturbations are perpendicular to the background magnetic field i.e. transverse, so they do not increase the magnetic field strength, and they transport energy along the direction of magnetic field lines.

Inside the magnetosphere both these waves have approximately the same speed: the Alfvén speed $v_A = B/\sqrt{\mu_0 \rho}$ where B is the magnetic field strength, ρ is the plasma mass density and $\mu_0 = 1.2566 \times 10^{-6}$ m kg s^{-2} A^{-2} is the permeability of free space/magnetic constant. Therefore the wave speed (and thus the frequency of for example any resonances) depends on both the magnetic field and the amount of plasma present, both of which change with location and time throughout the magnetosphere in ways that we still don't fully understand yet.

> **Exercise:** At geostationary orbit magnetic field strengths of $\sim$90 nT and proton number densities of $\sim$10 cm^{-3} are typical. What is the wave speed under these conditions?

It is worth mentioning that the majority of the dynamic solar wind – magnetosphere interaction is invisible, bar phenomena such as the aurora, thus much of our understanding of magnetospheric processes come from **spacecraft/satellites** in orbit around the Earth which can directly measure the particles and fields. There are still many aspects about these waves we do not know. For example, the variability in the frequency of different types of magnetospheric resonances (such as those shown in Figure 2) are not well understood. You will therefore be investigating various aspects of ULF waves in the magnetosphere through the use of spacecraft observations at geostationary orbit.

> **Exercise:** Field lines near the dayside magnetopause are typically about 16 R_E long, where 1 R_E = 6378.1 km is the radius of the Earth. Using your Alfvén speed from earlier and assuming a constant wave speed over the entire field line, estimate the

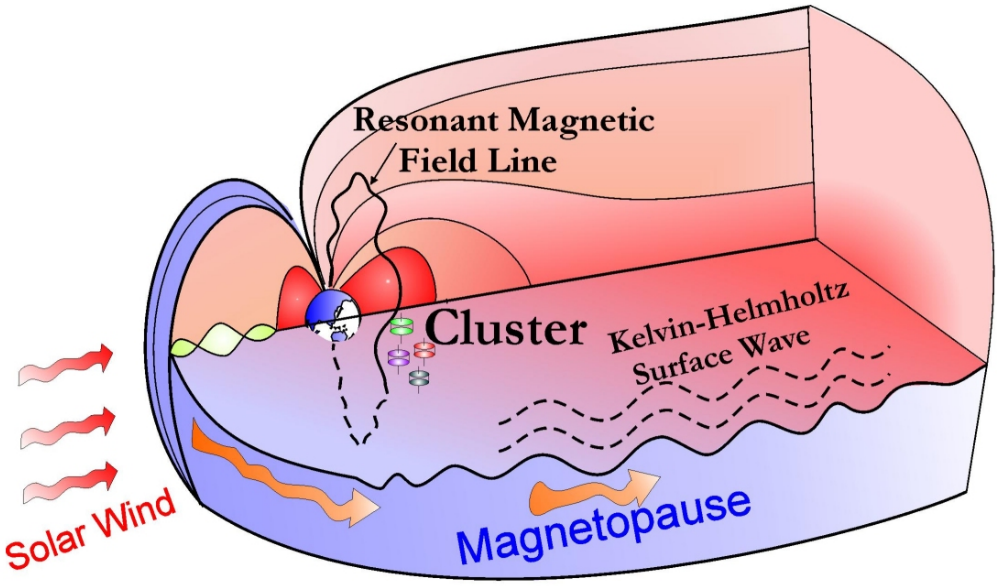

Figure 2: Illustration of some of the ULF wave modes supported by Earth's magnetosphere highlighting the variety present and hence why it remains an active area of research.

fundamental frequency of standing Alfvén waves on these field lines as illustrated in Figure 2.

Exercise: Standing magnetosonic waves can also form, as shown in green in Figure 2. Assuming a typical distance between boundaries of $6\,\mathrm{R_E}$ and that the outer boundary is open (an anti-node) whereas the inner boundary is fixed (a node), estimate the fundamental frequency of these waves again assuming constant speed.

2 Data

The Geostationary Operational Environmental Satellites (GOES) are a series of spacecraft in geostationary orbit above North America. They are equipped with Space Environment Monitoring Subsystems (SEMS), which include a **magnetometer** for measuring changes to the magnetospheric magnetic field, useful for both research purposes and in monitoring/forecasting space weather.

An example of the GOES spacecraft which were available in 2008 is given in Table 1, listing their location in longitude as well as how to calculate their local time (LT). Local time essentially measures position relative to the Sun (think about why we have time zones for instance). Therefore, a local time of 12h/noon means the spacecraft is directly between the Sun and the Earth; whereas a local time of 00h/midnight means the spacecraft is behind the Earth compared to the Sun. See Figure 3 for an illustration. In geostationary orbit this is a very easy quantity to calculate as the spacecraft orbit at the same rate as the Earth's rotation, so there is a direct link between Universal Time (the standard time used in science, a modern continuation of Greenwich Mean Time) and the spacecraft's Local Time.

GOES magnetometer data can be used to research ULF waves in Earth's magnetosphere since the magnetic field moves with the plasma. In this project you will be undertaking such a study using the novel approach of actually listening to these waves. This is because, unlike many automated computer algorithms, the human auditory system is perhaps the best pattern

Spacecraft	G10	G11	G12
Geographic Longitude	60° W	135° W	75° W
$LT\,[h] = UT\,[h] +$	-4	-9	-5

Table 1: Summary of the three GOES spacecraft which were available during 2008. The full spacecraft locations with year are contained within the provided spreadsheet.

recognition system that we know. In order to make the f_{real} =0.5–244 mHz waves audible to human ears though, the data has had to be rescaled in time

$$t_{audio} = t_{real}/(F_s \times \Delta t_{real}) \tag{1}$$

and thus also frequency

$$f_{audio} = f_{real} \times F_s \times \Delta t_{real} \tag{2}$$

where $F_s = 44,100$ Hz is the sampling frequency of the audio file and $\Delta t_{real} = 2.048$ s is the time resolution of the magnetometer data used. This rescaling converts an entire year of magnetic field measurements into an audio file less than 6 min long.

> **Exercise:** Calculate how long an entire day in is in the audio files.
>
> **Exercise:** If the time in the audio are quoted in seconds to either one, two or three decimal places, what level of accuracy does this correspond to in real time?
>
> **Exercise:** Calculate the date and local time of G11 in 2008 at 3m24.054 s into the audio.

You can use the provided **spreadsheet** to automatically do these conversions from now on. The filename of your audio files are in the format:

`g10_2008_Ball_10nT_diff.ogg`

- `g10`: which spacecraft the data is from
- `2008`: the year the data is from
- `B___`: magnetic field data in the following co-ordinates
  - `pol` = poloidal component which points radially outwards from Earth
  - `tor` = toroidal component which points eastwards
  - `com` = compressional which points along the magnetic field
  - `all` = a combination of all three with `pol` in the left channel, `tor` in the right and `com` shared between both. This is good for initially listening to the data.
- `10nT`: the data has been divided by this amplitude factor to give dimensionaless waveform units between -1 and 1
- `diff`: if present the data has been differenced in time to make spectograms clearer

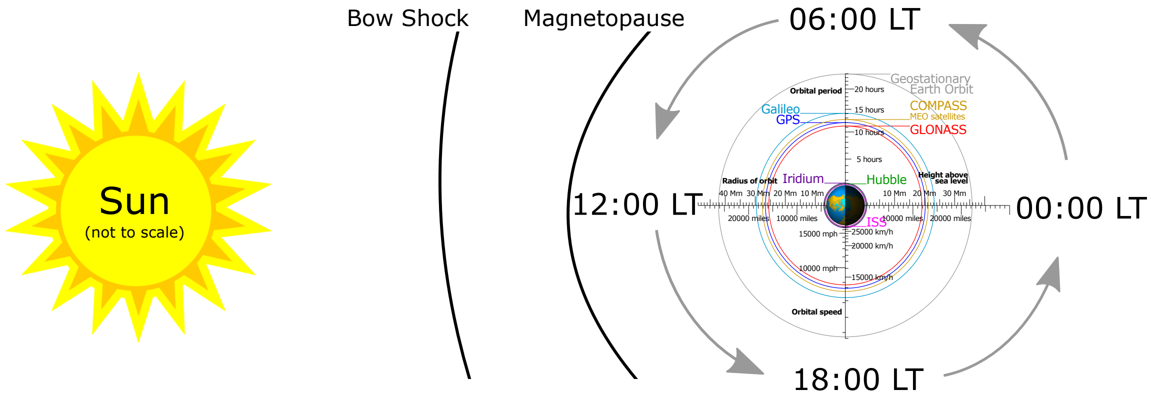

Figure 3: Diagram looking down on Earth's North Pole, demonstrating local time (LT) as a measure of position relative to the Sun.

3 Method

You will be using an audio editing package, **Audacity**, to listen to and analyse the magnetic field data provided. If this software is not installed on your computer, you can download a portable version at http://portableapps.com/apps/music_video/audacity_portable.

Audacity allows you to look at audio either as a waveform or as a spectrogram (a visual representation of the spectrum of frequencies in the audio as they vary with time). For the latter, you should (at least initially) use the log(f) spectrogram view since this is closer to how we interpret sounds ourselves and also allows you to clearly see the full range of frequencies from low to high. You may need to change some of the Preferences (in the Edit menu of Audacity) to show the ULF waves more clearly e.g. Window Size=1024, Maximum Frequency=20000 Hz, Gain=0 dB, Range=60 dB.

Note that the differenced waves (i.e. those with "diff" in the filename) will show the clearest spectrograms, whereas the original ones (i.e. without "diff") will show the clearest waveforms. It may therefore be beneficial in your analysis to import both of these tracks into Audacity and mute one of them, as displayed in Figure 4.

In your analysis you may wish to use a number of Audacity's tools and effects, for example:

- `Analyze > Contrast`: This can be used to measure the root mean square (RMS) of the selected audio, a measure of the overall volume/amplitude.
- `Analyze > Plot spectrum`: Quantifies the amount of signal at each frequency for the selected audio, which can be used to find any clear peaks at specific frequencies.
- `Effects > Spectral edit multitool`: By making a selection in frequency and time in spectrogram view, you can filter out unwanted signals. This may be useful if multiple signals at different frequency ranges are present. If this isn't available, you can do the same using low and high pass filters.
- `Effects > Noise Reduction`: By providing a sample of noise or unwanted signals, these are reduced thereby making other signals more prominant.

You should read the Audacity Manual (see section 5) for more details on all these tools/effects and others. Be careful not to overwrite your audio file with any changes you may make to it in the analysis process.

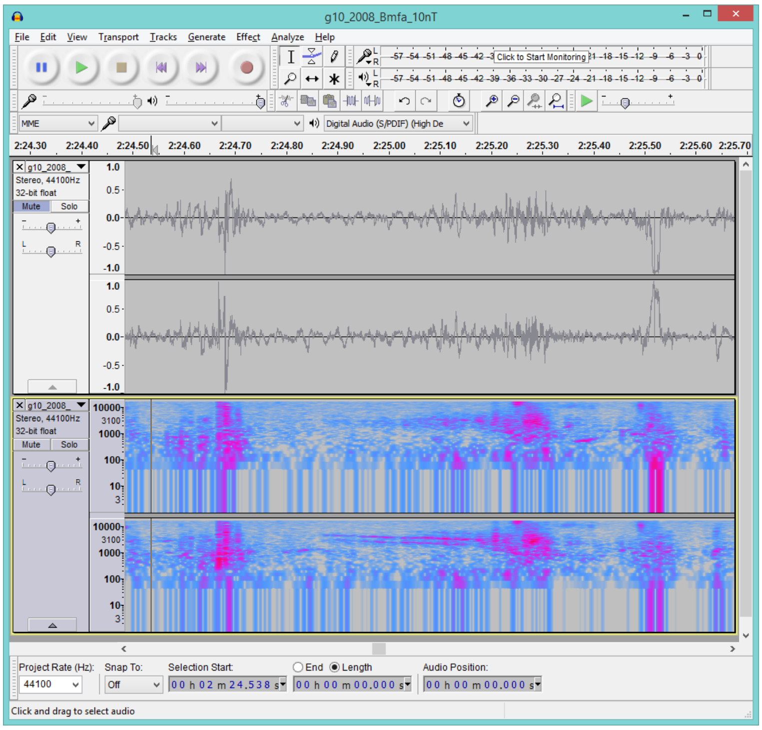

Figure 4: View in Audacity with the original waveforms shown in the top panels and the log(f) spectroview of the differenced waves in the bottom panels.

You may wish to add labels/markers for any events/sounds you find. This can be done by pressing `Ctrl+M` to add one at the playback position, i.e. when you're listening to the audio, or `Ctrl+B` to add a marker to the selected audio. Note that you can add text to your markers as a description.

4 Research

You will be conducting independent research into magnetospheric ULF waves and oscillations.

4.1 Initial Activities

As a first step you should simply listen to some of the sonified magnetic field data to get accustomed to what it sounds like and how to use Audacity. So pick a year and spacecraft and listen to one of the files to start with. Below are some suggested things to try:

- Pick a distinct sound and characterise it.
  - How would you describe the sound?
  - How loud is it? What is its amplitude (remember the original waveforms have been divided by an amplitude factor)?
  - Look at the spectrogram or plot a spectrum. Does it have a well defined frequency or set of frequencies/harmonics? Or does the sound occur over a wide range of frequencies?
  - Does the frequency or amplitude change as part of the sound?
  - Is the wave predominantly poloidal, toroidal or compressional?

- Try to identify at least three different types of wave events / sounds that are present?
  - How would you describe the sounds?
  - Look at the spectrogram or plot a spectrum. Can you relate how the waves sound to the different types of spectra?
  - Where do these waves occur in local time? e.g. are they around for example dawn (06:00), noon (12:00), dusk (18:00) or midnight (00:00)?
  - How long until the next similar event occurs?
- Is there an identifiable daily cycle in the ULF activity?
  - Where in local time do they occur?
  - How variable is this cycle from day to day?

4.2 Independent Research

In your research groups you should now decide what it is you'd like to research using the sonified magnetic field data. This can build on some of the sounds you worked on in the initial activities. You should attempt to identify, analyse and catalogue ULF events which fit within your chosen topic. Here are few ideas or approaches you may wish to take in your research:

Approaches

- **Case studies:** You may wish to focus on just one event or a handful of similar ones. You should then perform thorough analysis on it to fully characterise the wave's properties and location, looking for the same event at the different spacecraft to get a feel for size, and trying to find out what conditions were present during the wave. These types of studies are particularly important for rare events.
- **Statistical surveys:** Ideal for wave events that occur many times within the data, statistical studies can help us understand how often and where similar events occur and what range of properties they have. You should decide what aspect(s) of the waves you'd like to investigate in this manner and attempt to build up a comprehensive picture of these aspects of the waves over the course of the year-long data file, or indeed across multiple years if you have time.
- **Surveying Specific Conditions:** You may wish to take a converse approach, rather than going through the ULF data to find events, you could choose a specific set of solar wind or magnetospheric conditions or previously identified events and then investigate the magnetosphere's ULF activity for these.

Potential Topics

- When and where do specific types of wave events occur?
- How variable are the frequencies of certain types of wave events?
- When or how often do large amplitude ULF events occur?
- What were the causes of certain wave events?
- How effective are different solar wind structures or features at driving ULF waves?

You do not have to follow one of these approaches or topics, though do discuss thoroughly in your group and also with your teacher before getting started with your research. Be sure to collate all your results on ULF wave events into the **provided spreadsheet template**. Enter your data into the white boxes, these will automatically calculate the dates, times and local times for you to save effort. You will likely, however, need to add extra columns depending on your research topic so discuss what information it is you need. You may also wish to use Audacity's editing tools to save clips of specific types of events for cataloguing and/or presenting your findings.

Remember, that this is a taste of real research so you will get stuck and the answers may not be known. This is why it is important to persevere, discuss in your groups and with your teacher how to overcome any problems and if you're still stuck your teacher can get in touch with researchers in this area who can provide assistance.

5 Useful links

Audacity manual: http://manual.audacityteam.org/o/index.html
SSFX (Space Sound Effects) project (videos): http://ssfx.qmul.ac.uk
Dr Archer's PhD Thesis (suggest only the first few chapters): https://spiral.imperial.ac.uk:8443/handle/10044/1/24743
GOES magnetometers: http://www.swpc.noaa.gov/products/goes-magnetometer
Geomagnetic pulsations: https://wiki.oulu.fi/display/SpaceWiki/Geomagnetic+pulsations
Magnetic Pulsations (comprehensive): http://www.whoi.edu/science/AOPE/emworkshop/pdf/mcpherron.pdf
Magnetospheric ULF waves: http://www-ssc.igpp.ucla.edu/gem/IAGA_Div3/2011_Menk_ULF.pdf
Sonification of data: http://dx.doi.org/10.1063/PT.3.1550
Standing Alfvén waves at geostationary: http://onlinelibrary.wiley.com/doi/10.1029/2009JA015243/abstract